Micro-magnetic Actuators

Session-14

(Source: Chapter 8, Liu & Chang)

Micro-magnetic Actuators

- *micro* magnetic actuators, which often involve permanent magnets and electromagnetic coils
- Magnetic sensors (including location sensors) are important for data storage, consumer electronics, and industrial applications.
- The magneto-resistive effects and the Hall Effect are the most commonly used principles of magnetic field sensing.
- Indeed, many materials, components, and fabrication methods for micro actuators originated in the magnetic sensing and disk storage industry

Magnetic field intensity (Symbol H) represents the driving magnetic influence external to a magnetic material. Its convenient SI unit is A/m. The conventional unit in CGS unit system is oersted ($1\ \text{A/m} = 4\pi/10^3\text{Oe}$).

Another term, called **magnetic field density** (Symbol B), represents the induced total magnetic field inside a piece of magnetic material. The total magnetic field accounts for the influence of the induction field and the internal magnetization. The term B is often referred to as magnetic induction or magnetic flux density as well. The magnitude of B can be expressed in units within the SI unit system: Tesla, or Wb/m^2, or within the CGS unit system: Gauss ($1T = 10^4$ Gauss). The convenient SI unit for Weber is $V \cdot s$. The convenient SI unit for Tesla is therefore $V \cdot s/\text{m}^2$.

The magnetic field densities of commonly encountered magnetic objects are:

- common refrigerator magnet: 100–1000 Gauss;
- rare earth magnet used in Magnetic Resonance Imaging:1–2 T;
- magnetic storage media: 10 mT, or 100 Gauss;
- earth magnetic field (near equator):1 Gauss.

The relationship between B and H can be described using the following equation:

$$B = \mu_0 H + M = \mu_0(H + \chi H) = \mu_r \mu_0 H \qquad (8.1)$$

A magnetic field may cause internal magnetic polarization of a piece of magnetic material within the field which is called **magnetization**

FABRICATION OF MICRO MAGNETIC COMPONENTS

- Although it is possible to attach small pieces of magnetic materials to micro mechanical structures for realizing sensors and actuators, this process is generally very inefficient.
- Monolithic integration of magnetic materials is more accurate and widely practiced.
- The most common technique for depositing ferromagnetic materials for micro devices applications is **electroplating**.
- A chemical solution consisting of constituent ions of the desired magnetic material is used as a wafer bath.
- The work piece for metal deposition (wafer) is biased negatively with respect to a counter electrode, which is placed in the bath during the electroplating session.

FABRICATION OF MICRO MAGNETIC COMPONENTS

- In many cases, the wafer is not conductive on its own. Under these circumstances, the surface of a wafer is first coated with a thin film metal layer for providing negative electric biasing.
- This thin film layer is called the **seed layer**. Common seed layer materials are copper, aluminum, or gold.
- Thin metal layers of Cr or Ti are often used to enhance adhesion between the seed layer metal and the substrate.

FABRICATION OF MICRO MAGNETIC COMPONENTS

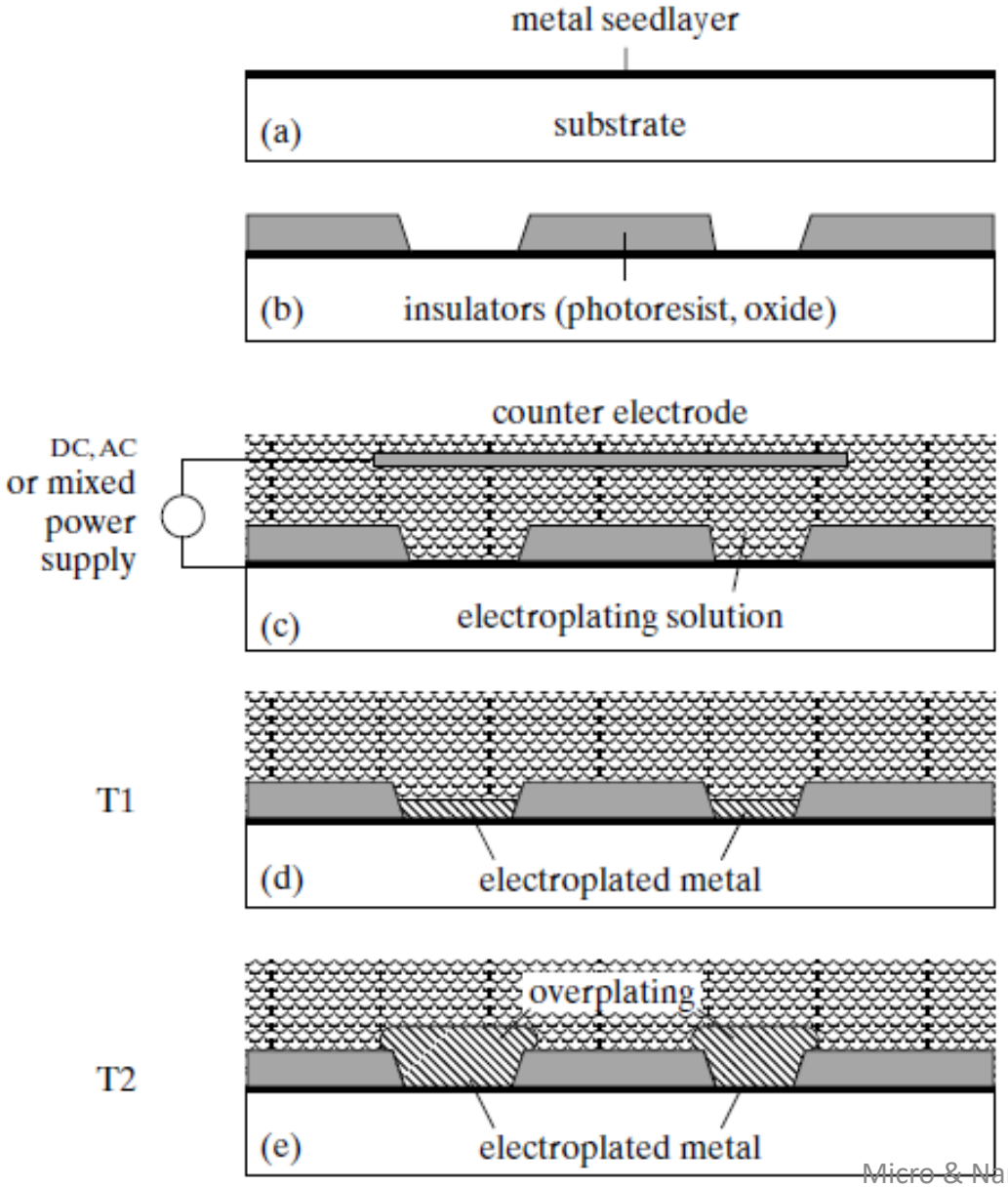


FIGURE 8.6

A process for electroplating of magnetic materials

A typical electroplating process flow using a seed-layer is shown in Figure 8.6. A substrate covered with a metal seed layer is prepared. In order to produce patterned ferromagnetic thin film, a mold electroplating method is often used (Figure 8.6a). The mold, made of a thin film insulating layer (e.g., patterned photoresist), is deposited and patterned (Figure 8.6b). The wafer is immersed in an electroplating solution (Figure 8.6c). Electroplated metal grows in the open windows, where the seed layer is exposed to the electroplating bath (Figure 8.6e). The electroplating mold is then selectively removed. The electroplating process may result in thickness smaller than the height of mold (Figure 8.6d), or greater (Figure 8.6e), depending on the duration of the plating step. When the thickness of electroplated metal reaches beyond the height of the mold, it tends to grow laterally. This property can be used to create metallic structures with unique shapes, such as the mushroom in Figure 8.7.

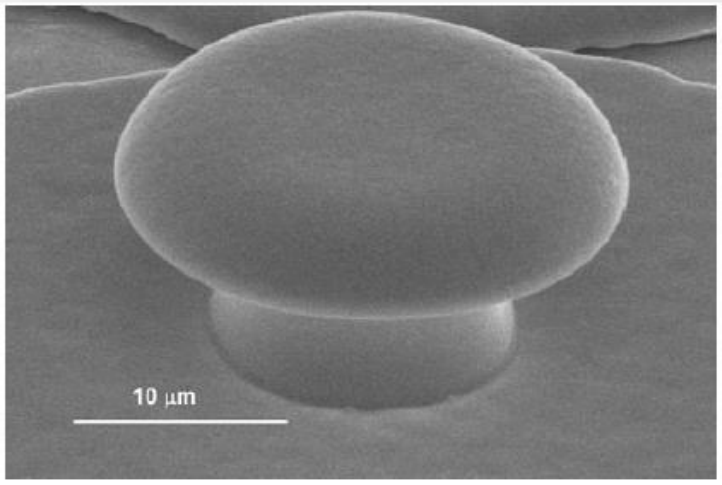


FIGURE 8.7
Mushroom shaped electroplated metal, revealed after the electroplating mold is removed.

Micro-solenoid Synthesis

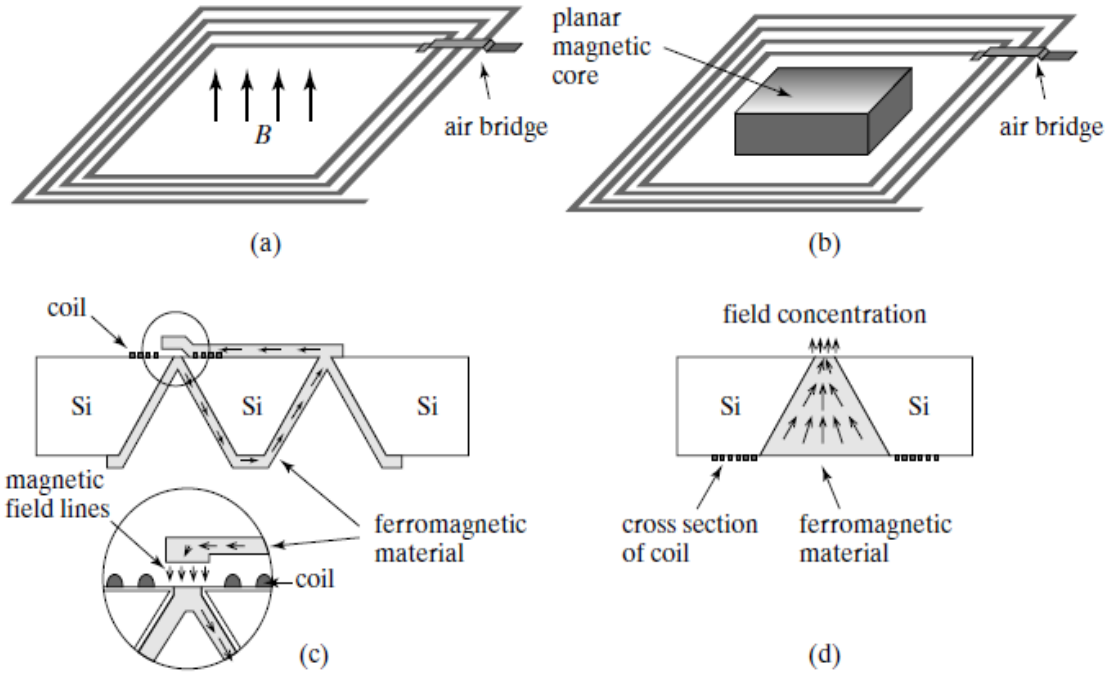


FIGURE 8.9

A planar magnetic inductor.

- A number of techniques for realizing micro solenoids with integrated ferromagnetic core are shown in Figure 8.9.
- The simple scheme of electroplating a high-permeability magnetic material with a planar coil improves upon the performance of a single layer magnetic coil (Figure 8.9b).
- However, the improvement is not significant as the issue of strong dispersion of magnetic filed persists.
- To contain and even concentrate the magnetic field lines, innovative structures and fabrication processes are involved.
- For example, through-wafer magnetic cores can be built by taking advantage of the sloped surfaces created using anisotropic etching (Figure 8.9c).
- The equivalent of horse-shoe magnet can be made by processing magnetic core materials on both sides of a wafer.
- It has been shown that 200 mN of actuation force can be generated with a 80 mA actuation current and 320 mW of power.
- The magnetic flux density can be increased by reducing the cross-sectional area of the core (Figure 8.9d).

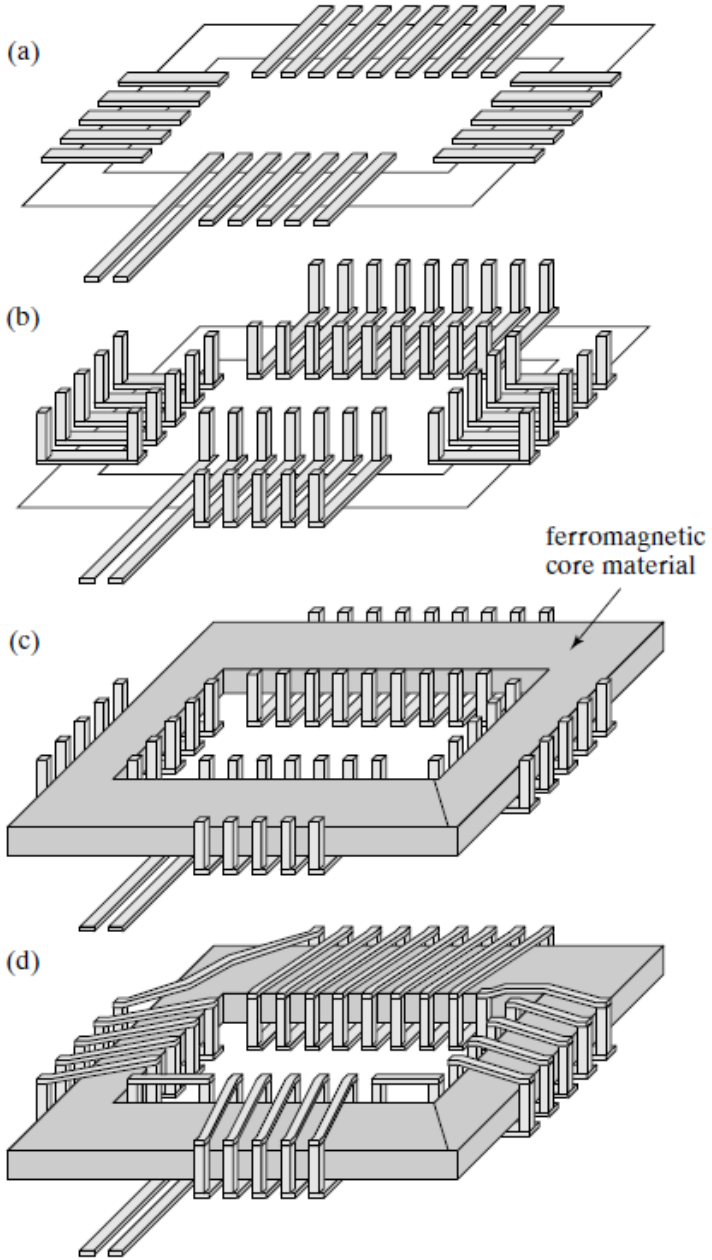


FIGURE 8.11

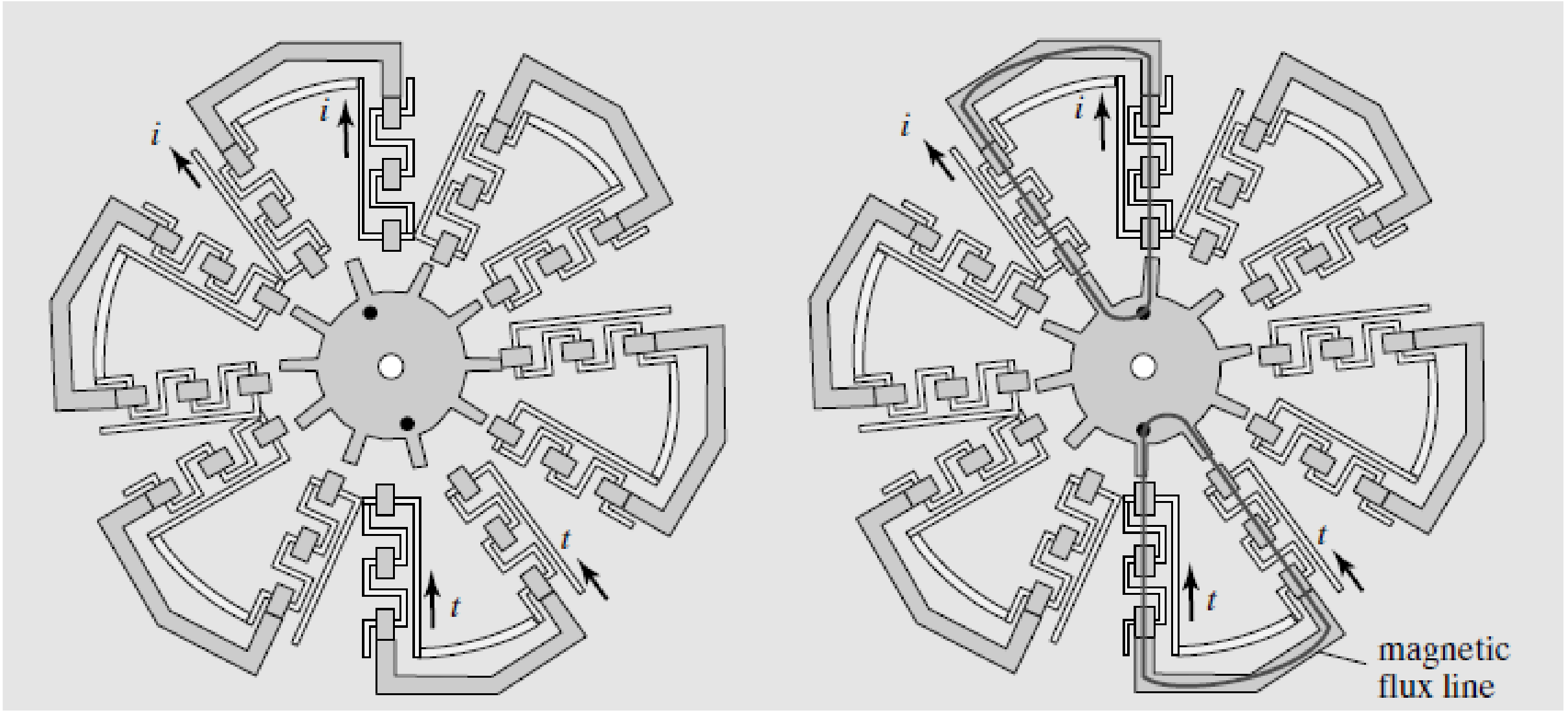
Fabrication of three-dimensional micro coil.

Case 8.1 Magnetic Motor

The first example is a planar variable-reluctance magnetic micromotor with fully integrated stator and coils [23] (Figure 8.12). The stators are made of integrated electromagnets, whereas the rotor is made of a soft magnetic material. The motor has two sets of salient poles, one set in the stator (which usually has excitation coils wrapped around the magnetic poles) and another set on the rotor.

When a phase coil is excited, the rotor poles located closest to the excited stator poles are attracted to the stator pole (Figure 8.12a,b). Due to the rotation of the rotor, the said rotor poles will align with the stator poles. The excited phase coil is turned off, and the next phase is excited for continuous motion. In this design, the wound poles of all phases are arranged in pairs of opposite polarity to achieve adjacent pole paths of short lengths. The stator coils arranged in one or more sets and phases are excited in sequence to produce continuous rotor rotation.

The rotor is 40 μm thick and 500 μm in diameter. It is micro assembled onto the chip containing the stators or fabricated in an integrated fashion by electroplating. When a 500-mA current is applied to each stator, 12° of rotation (one incremental stroke) is produced. By applying three phase 200-mA current pulses to the stators, rotation of the rotor was observed with speed and direction adjusted by the frequency and phase firing order of the power supply. Continuous rotor motion at speed up to 500 rpm has been observed. The predicted torque for the motor at 500-mA drive current is calculated to be 3.3 nN-m.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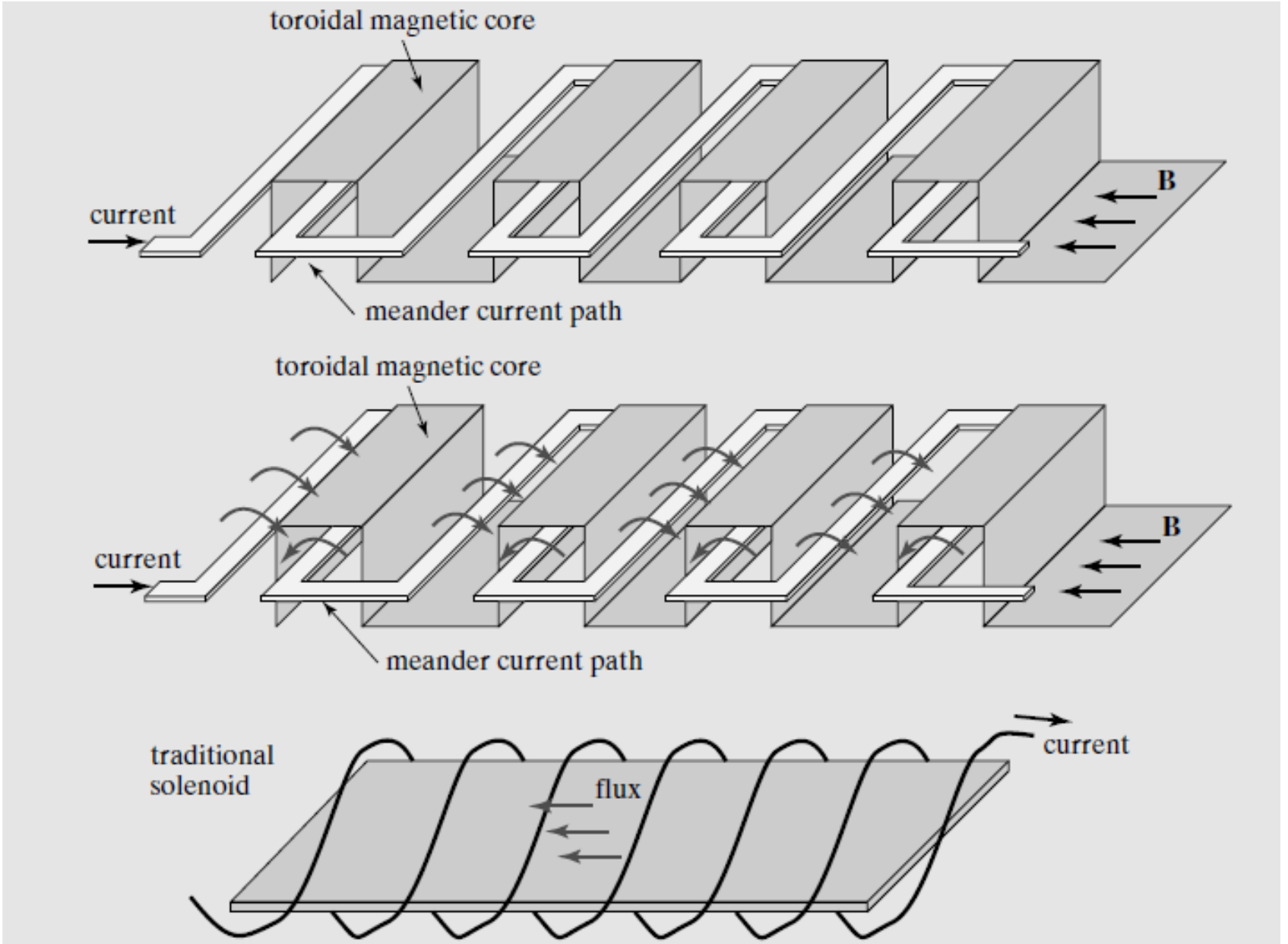

FIGURE 8.12

A variable-reluctance magnetic micro motor.

Case 8.2 Magnetic Beam Actuation

One of the most unique performance characteristics of magnetic actuation over electrostatic, thermal, and piezoelectric actuators is the ability to generate *torque* and achieve large angular displacement. For example, large angular displacement, and hence, vertical displacement on the order of 90° and several millimeter can be achieved under a magnetic field of 10 kA/m [5].

One actuator has been developed for dynamic aerodynamic control [24]. The actuator consists of a rigid flap supported on one side by two fixed-free cantilevers. Each flap is made of polycrystalline silicon (as the support structure) and electroplated ferromagnetic materials (Permalloy in this case). The cross-sectional side view is shown in Figure 8.14a. When an external magnetic field is present, an internal magnetization is developed in the ferromagnetic piece. The situation is similar to the one experienced by piece #4, case c of Figure 8.5. Experimental characterization of a single flap has been conducted to show that up to 65° angular displacement can be achieved.

The magnitude of the internal magnetization equals the saturation magnetization, being approximately 1.5 T for the prepared material. The direction of the internal magnetization vector lie within the plane of the flap according to shape anisotropy (Figure 8.14b).

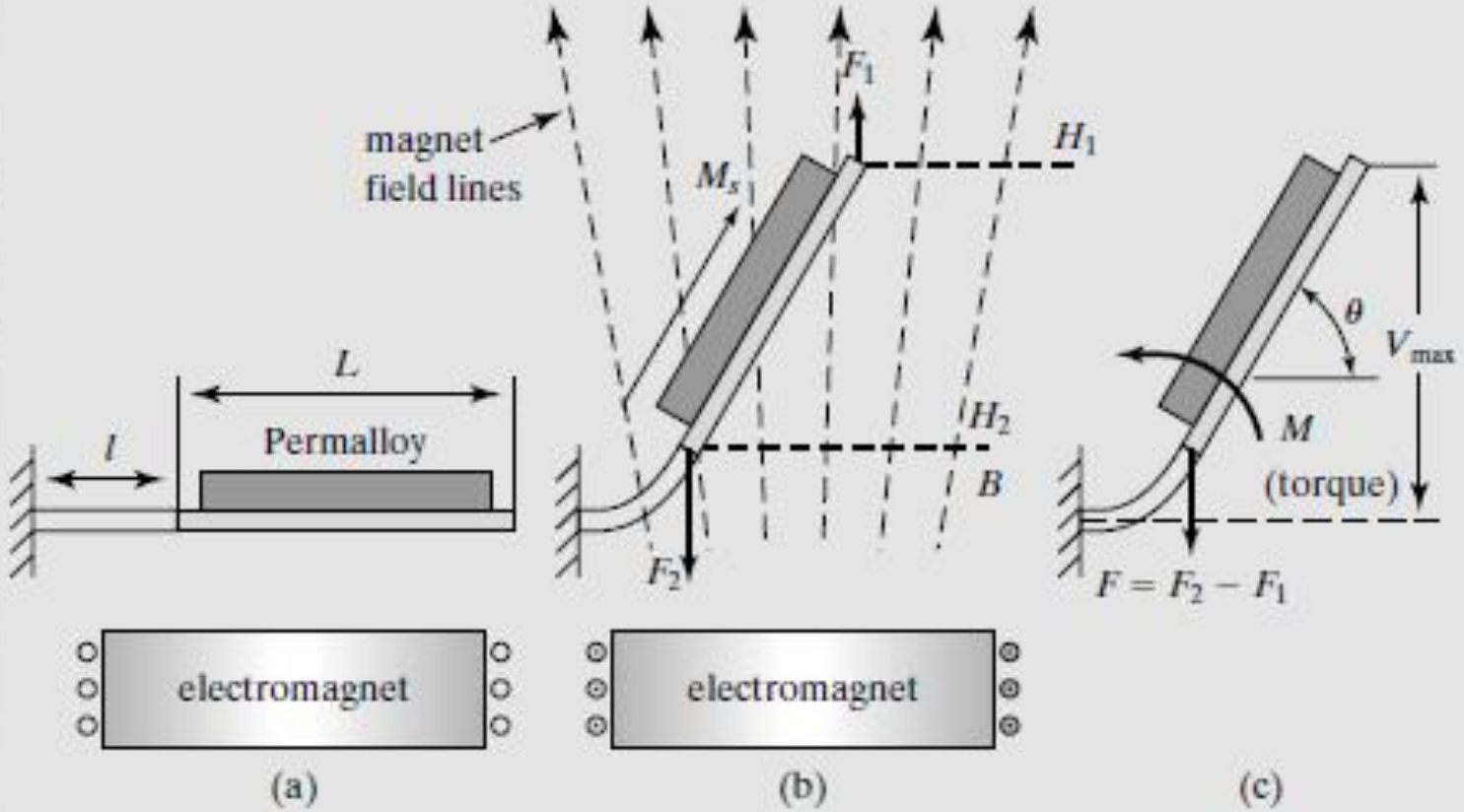

FIGURE 8.14

Flap magnetic actuator.

Case 8.3 Plate Torsion with Lorentz Force Actuation

A moving-coil electromagnetic optical scanning mirror capable of one-axis rotation is discussed here (Figure 8.16). A mirror plate is supported by torsional hinge structures consisting of multilayered polyimide films with aluminum lead wires in between. The mirror consists of a planar micro plate, with a smooth side for optical reflection and the opposite side hosting a planar coil. Two permanent magnets are placed on the side of the mirror, such that the magnetic field lines are parallel to the plane of the mirror and orthogonal to the torsional hinges. When current passes through the coil, Lorentz forces will develop and cause rotational torque on the mirror. The direction of the torque depends on the direction of the current input.

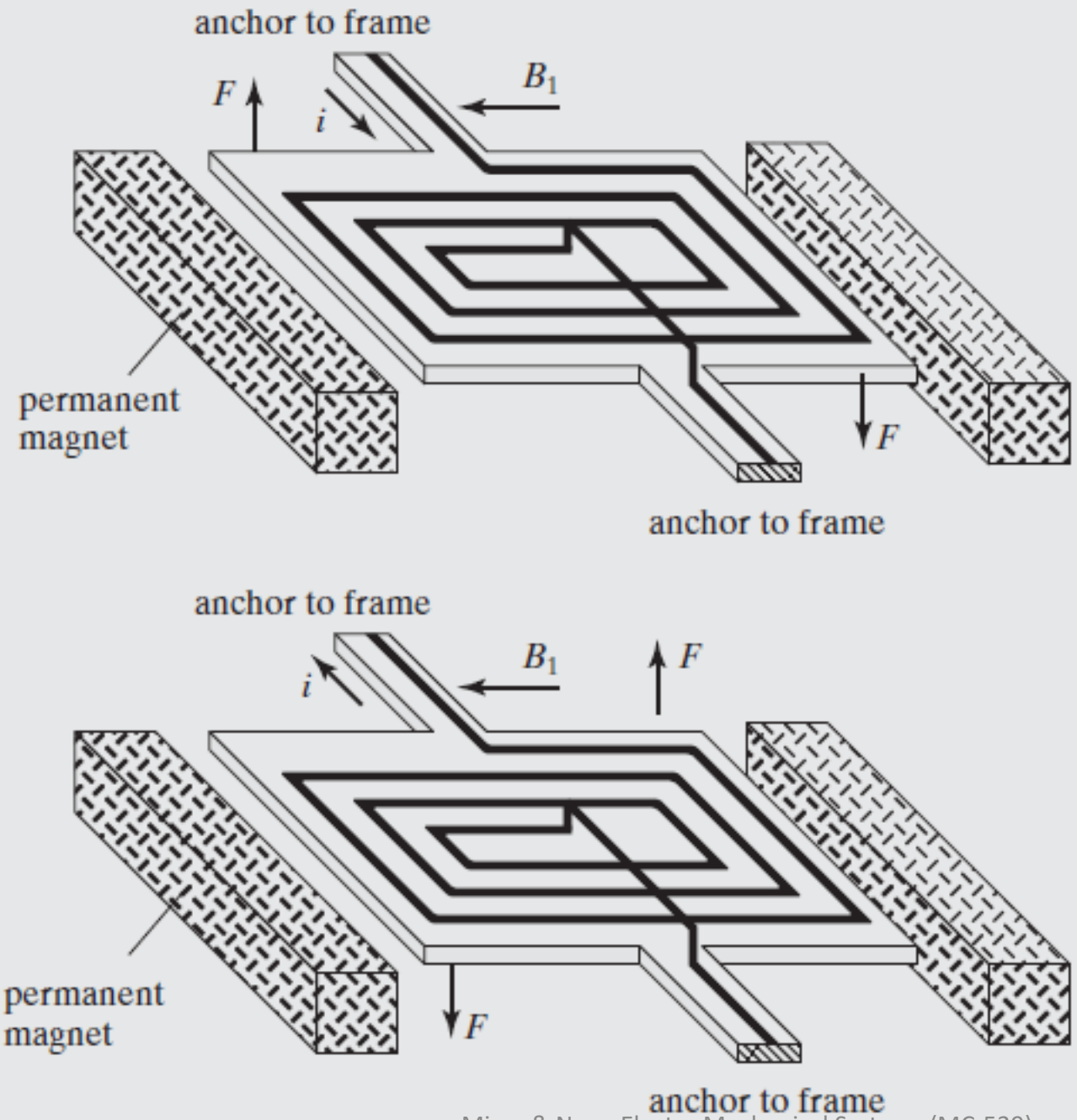

FIGURE 8.16

Diagram of a micro mirror.

Problem 6: Design

A 1-mm-long polysilicon wire with width and thickness being 2 μm is fixed on both ends. Find the maximum displacement occurring on the wire when the applied transverse magnetic field is 0.1 T. A DC current of 1 mA is applied through the wire.

Problem 7: Design

Determine the magnetic field generated by a solenoid with multiple wire winding. The number of windings is 200, while the core has a cross-sectional dimension of 200 μm by 50 μm. The current is 10 mA. The diameter of the wire is 10 μm.

Summary of Sensing and Actuation Methods

(Chap: 9, Liu & Chang)

- A developer of micro sensors and actuators face many choices and obstacles.
- The selection of sensing and actuation methods is dependent on many factors, including performance, stability, reliability, energy consumption, cost and complexity of instrumentation, cost of development, and price.
- It is rare that a sensing or actuation mechanism prove to be advantageous for all selection criteria.

TABLE 9.1 Comparison of various sensing methods.

	Advantages	Disadvantages
Electrostatic sensing	• Simplicity of materials; • Low voltage, low current operation; • Low noise; • Rapid response.	• Large footprint of device necessary to provide sufficient capacitance; • Sensitive to particles and humidity.
Thermal sensing	• Simplicity of materials; • Elimination of moving parts.	• Relatively large power consumptions; • Generally slower response than electrostatic sensing.
Piezoresistive sensing	• High sensitivity achievable; • Simplicity of materials (metal strain gauge).	• Requires doping of silicon to achieve high-performance piezoresistors; • Only allow doping front-facing surfaces; • Sensitive to environmental temperature changes.
Piezoelectric sensing	• Self-generating—no power necessary.	• Complex material growth and process flow; • Relative poor DC response due to electric leakage across the material; • Piezoelectric material cannot sustain high-temperature operations.

TABLE 9.2 Comparison of various actuation methods.

	Advantages	Disadvantages
Electrostatic actuation	• Simplicity of materials; • Fast actuation response.	• Trade-off between magnitude of force and displacement; • Susceptible to pull-in limitation.
Thermal actuation	• Capable of achieving large displacement (angular or linear); • Moderately fast actuation response.	• Relatively large power consumption; • Sensitivity to environmental temperature changes.
Piezoelectric actuation	• Fast response possible; • Capable of achieving moderately large displacement.	• Requires complex material preparation; • Degraded performance at low frequencies.
Magnetic actuation	• Capable of generating large angular displacement; • The possibility of using very strong magnetic as bias.	• Moderately complex processes; • Difficulty to form on-chip, high-efficiency solenoids.